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Financial viabilities of husk-fueled steam engines as an energy-saving technology in Thai rice mills

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Abstract

Rice husk generated as a by-product of rice milling process can be utilized as an energy source for rice mills. The advantages of applying the steam engine as a power source for rice mills are discussed. An economic model was developed to find out the internal rate of return, IRR, on the investment in steam engine's as an energy-saving technology in Thai rice mills. Based on the technical and economic data presented in this study, rice mills from 45 to 120 t d^{-1} in size are financially feasible for investments in steam engines as an energy-saving technology for the mills. The maximum affordable husk prices at the different levels of mill use for various sizes of rice mill were analyzed and the economic performance of higher efficiency technology was also tested in this study.

Keywords: Rice husk; Rice mill; Steam engine; Feasibility study; Biomass energy

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Nomenclature

CF_n	cash flow in the year nth, THB
$C_{f,n}$	fuel cost in the year nth, THB yr^{-1}
$C_{l,n}$	labor cost in the year nth, THB yr^{-1}
$C_{OM,n}$	operation and maintenance cost in the year nth, THB yr^{-1}
HPR	Husk-to-paddy ratio, decimal
e_{CO_2}	carbon-dioxide emission factor of using electricity, kg kW h^{-1}
$e_{d,e}$	electrical rice-mill specific electricity demand, kW t^{-1} d
$e_{d,s}$	steam engine rice-mill specific electricity demand, kW t^{-1} d
$e_{e,e}$	electrical rice-mill specific electricity consumption, kW h t^{-1}
$e_{e,s}$	steam engine rice-mill specific electricity consumption, kW h t^{-1}
D	demand saving, kW
E	energy saving, kW h yr^{-1}
f	inflation rate, decimal
f_e	energy charge inflation-rate, decimal
H	operation hours, h yr^{-1}
h_g	vaporization enthalpy of water at 25 °C, kWh kg^{-1}
IN_n	total income in the year nth, THB yr^{-1}
INV_e	investment of electrical rice-mill, THB
INV_s	investment of steam engine rice-mill, THB
L_e	number of worker's in electrical rice-mill, person's
L_s	number of worker's in steam engine rice-mill, person's
LHV_d	lower heating value dry basis, kWh t^{-1}
LHV_w	lower heating value wet basis, kWh t^{-1}
MC_w	moisture content wet-basis, decimal
m_f	fuel consumption, t yr^{-1}
$m_{f,avai}$	available rice husk, t yr^{-1}
N	economic project life time, yr
NPV	net present value, THB
η_{th}	energy-conversion efficiency, decimal
OUT_n	total expenditure at the year nth, THB yr^{-1}
P	annual amount of paddy milled in the mill, t yr^{-1}
p_{ed}	price of electricity demand, THB kW^{-1} $month^{-1}$
$p_{ee,n}$	price of electric energy at the year nth, THB kW h^{-1}
$p_{h,n}$	price of rice husk in the year nth, THB t^{-1}
$p_{l,n}$	wage rate in the nth year, THB $man\text{-}day^{-1}$
$p_{om,n}$	operation and maintenance rate in the year nth, THB kW h^{-1}
Q	heat demand for steam-engine system, kWh yr^{-1}
r	economic discount rate, decimal
S	rice-mill capacity, t d^{-1}
u	mill use factor, decimal
ΔCO_2	reduction of carbon-dioxide emission, ton

1. Introduction

Rice farming is the largest agricultural sector in Thailand, both in terms of cropped area and its percentage of the GDP. Annual paddy production is approximately 20 million tons. Rice husk is one of the by-products of the rice-milling process. The annual production of rice husk is approximately 4.6 million tons [1]. Rice husk can be burned and the heat of combustion can be used as an energy source for rice mills. However, concerning rice mills, only 50.7% of the rice husk produced at the mills is currently being used as fuel [2]. Use of husk in industries other than rice processing involves the handling and transportation of this low bulk-density (112–144 kg/m^3) by product. On-site use of husks in the rice milling process, which requires mechanical energy, avoids the necessity of transportation.

Most of the rice mills require less than 1000 kW and the reciprocating steam-engine is suitable for power generation up to approximately 1000 kW [3]. A reciprocating steam-engine can be operated with saturated steam generated from a simple fire-tube boiler, which requires much lower investment and a less experienced plant operator than the water-tube boiler used in the steam-turbine system.

The husk-fired steam engine rice-mills are commercially available. In the steam engine rice-mill, the milling equipment is driven by the steam engine fueled by rice husks, while the milling equipment of electrical rice mills is driven by the electrical motor. Mechanical energy generated from the steam engine can replace the electricity consumption in the electrical rice-mill. Using husk-fired steam-engine rice-mills will benefit Thailand in several ways, including the reduction of dependency on imported energy, the reduction of carbon-dioxide emission's and the reduction of rice production cost due to lower electricity consumption in the milling process.

Recently, many new rice-mill owners select the electrical rice mill because of its simplicity in operation and lower investment compared to steam engine rice mills. However, some electrical rice-mill owners have suffered from higher production costs due to increases in the price of electricity. The systematic economic evaluation of husk-fueled steam-engine rice-mills compared to electrical rice-mills will provide useful information for rice-mill owners in selecting the appropriate system for their particular conditions.

The primary objective of this work is to present a systematic methodology for financial-feasibility evaluation of husk-fueled steam-engine rice-mills, as compared to electrical rice mills. The maximum affordable husk-price analysis was also made in order to see the effects of parameter variations on the economic performance.

1.1. Rice milling in Thailand

Rice milling involves the removal of husk and bran from rough rice to produce white rice. It is composed of two main units, dehusking and whitening. In steam-engine rice mill, the mechanical milling equipment, for example, the husker, whitener and polisher, are driven by a steam engine. In electrical rice mills, all equipment is powered by electricity. However, steam-engine rice-mills still require electricity for some functions, such as, the packaging machine, color sorter and lighting in the mill.

The Rice Millers Association of Thailand listed about 17,000 commercial and active rice mills in 1996. In recent years, the large rice-mills have increased their milling duration to about 11 months per year, 24 h a day [4]. It was reported that 93% of rice mills are smaller than 20 t d^{-1}, but 75% of paddies' production was milled in mills larger than 20 t d^{-1} [5].

1.2. Steam-engine rice-mill

In a steam-engine rice-mill, steam is generated by the heat of combustion from burning of rice husk at the boiler and steam is fed into a reciprocating steam-engine to generate mechanical power for driving the milling units. The main equipment of the steam-engine system, commonly used in the rice mill, is as follows.

1.2.1. Boiler

The boiler is the steam-generating equipment. Husk is burned in the furnace and the heat of combustion is transferred to evaporate water inside the boiler. Most boilers in the Thai steam-engine rice-mill are 3-pass fire-tube boilers with inclined step-grate furnaces. Air is supplied to the furnace by a natural draft generated by a very tall chimney. Most of them generate saturated steam at 10 bargs [6].

1.2.2. Steam engine

This is a slider-crank mechanism. Steam engines convert thermal energy, contained in steam, to mechanical power in the crank shaft of steam engine. The commonly-used steam-engines in Thai rice mills are double-acting single-cylinder steam engines. Each steam engine has two expansion stages: a high pressure and a low pressure stage. Their rotational speed is limited to lower than 120 rpm due to poor mechanical balancing of the dynamic mass. Most of them are horizontal arrangement engines, with a sliding-valve system. Lubricant is fed to the engine by mixing it with steam at an inlet valve.

The system matchings between the milling equipment, steam engine and boiler for various sizes of rice mill are given in Table 1.

Table 1
Specification of commonly used steam engine for various sizes of rice mills in Thailand [5]

Mill capacity (t d^{-1})	Steam engine			Boiler		
	Piston diameter (in.)		Stroke (in.)	Diameter (feet)	Length (feet)	Capacity (t h^{-1})
	High pressure	Low pressure				
35	7	10.5	7	3.5	18	0.696
45	7.5	11	7.5	3.5	20	0.767
55	8	12	8	4	20	0.841
60	8.5	12.5	8.5	5	20	1.052
70	9	13	9	5.5	20	1.156
95	10	15	10	6	25	1.578
120	12	18	12	6	30	1.893

2. Methodology

To evaluate the economic performance of steam-engine rice-mills throughout the entire project life, an economic model was developed for finding out the internal rate of return, IRR, of the additional investment in the steam engine rice-mill over the electrical rice-mill. By this objective, the IRR is not the IRR of the whole rice-mill investment but the IRR of the additional investment into a steam engine as an energy-saving technology for the rice mill.

The model begins with a fuel-availability analysis. Husk to paddy ratio, HRP, is used in estimating the availability of the fuel. The annual available rice husk is evaluated by Eq. (1). The fuel consumption, m_f, must not exceed the available rice husk, $m_{f,avai}$. The wet basis lower heating-value of rice husk is determined by Eq. (2)

$$m_{\mathrm{f,avai}} = 365Su \cdot \mathrm{HRP}, \tag{1}$$

$$\mathrm{LHV_w} = (1 - \mathrm{MC_w})\mathrm{LHV_d} - h_{\mathrm{fg}}\mathrm{MC_w}. \tag{2}$$

The annual cash flow, CF_n is the difference between the income, IN_n and the expenditure, OUT_n. The incomes and expenditures must be calculated every year throughout the project life. To include the effect of inflation rate, the terms $p_{\mathrm{ee},n}$, $p_{\mathrm{h},n}$, $p_{\mathrm{om},n}$ and $p_{\mathrm{l},n}$ are varied annually by the inflation rate, f. The subscript n indicates the nth year of the project.

$$\mathrm{CF}_n = \mathrm{IN}_n - \mathrm{OUT}_n. \tag{3}$$

The total annual income is derived from the saving of electricity demand and the saving of electrical energy as given in Eq. (4). The term p_{ed} (THB kW^{-1} month^{-1}) and p_{ee} (THB kWh^{-1}) are the buying prices of electricity on a demand basis and energy basis, respectively.

$$\mathrm{IN}_n = 12Dp_{\mathrm{ed}} + Ep_{\mathrm{ee},n}. \tag{4}$$

The saving of electricity demand depends on the mill capacity, S (t d^{-1}), and the difference of specific electricity demands between the electrical rice-mill and steam engine rice-mill, Δe_{d} (kW t^{-1} d). Mill use factor, u, was defined as the ratio between the actual amount of paddy milled in the mill, P (t yr^{-1}), and the maximum potential amount of paddy milled by the mill, as given in Eq. (5). The saving of electrical energy, E, depends on the difference of specific electricity-consumption between the electrical rice-mill and the steam engine rice-mill, Δe_{e} (kWh t^{-1}) and the amount of milled paddy, which depend on mill capacity, S, and mill use factor, u, as given by Eq. (9).

$$u = \frac{P}{365S}, \tag{5}$$

$$\Delta e_{\mathrm{d}} = e_{\mathrm{d,e}} - e_{\mathrm{d,s}}, \tag{6}$$

$$\Delta e_{\mathrm{e}} = e_{\mathrm{e,e}} - e_{\mathrm{e,s}}, \tag{7}$$

$$D = S\Delta e_{\mathrm{d}}, \tag{8}$$

$$E = 365S\Delta e_{\mathrm{e}}u. \tag{9}$$

Substitute D and E from Eqs. (8) and (9) to Eq. (4) to obtain the annual income as

$$\mathrm{IN}_n = S[12p_{\mathrm{ed}}\Delta e_{\mathrm{d}} + 365p_{\mathrm{ee}}u(1+f_{\mathrm{e}})^n\Delta e_{\mathrm{e}}]. \tag{10}$$

The annual expenditure, OUT_n, as given by Eq. (11), comprises three components, namely the fuel cost, $C_{\mathrm{f},n}$, due to the loss of opportunity to sell husk, additional operation and maintenance cost,$C_{\mathrm{OM},n}$, and the additional labor cost, $C_{\mathrm{l},n}$, given by Eqs. (12)– (20). The annual operation hours, H relate to the mill use factor. However, the mills are not always operated at the mill capacity, S. In taking this into account, the operation hours factor is estimated by the mill-use factor, u, plus 0.1, as given in Eq. (19).

$$\mathrm{OUT}_n = C_{\mathrm{f},n} + C_{\mathrm{OM},n} + C_{\mathrm{l},n}, \tag{11}$$

$$C_{\mathrm{f},n} = m_{\mathrm{f}}p_{\mathrm{h},n}, \tag{12}$$

$$m_{\mathrm{f}} = \frac{Q}{\mathrm{LHV_w}} = \frac{E}{\eta_{\mathrm{th}}\mathrm{LHV_w}}, \tag{13}$$

$$C_{\mathrm{f},n} = \frac{365S\Delta e_{\mathrm{e}}u[p_{\mathrm{h}}(1+f)^n]}{\eta_{\mathrm{th}}\mathrm{LHV_w}}, \tag{14}$$

$$C_{\mathrm{OM},n} = Ep_{\mathrm{om},n}, \tag{15}$$

$$C_{\mathrm{OM},n} = 365S\Delta e_{\mathrm{e}}u[p_{\mathrm{om}}(1+f)^n], \tag{16}$$

$$\Delta L = L_{\mathrm{s}} - L_{\mathrm{e}}, \tag{17}$$

$$C_{\mathrm{l},n} = H\Delta L\frac{p_{\mathrm{l},n}}{8}, \tag{18}$$

$$H = 8760(u+0.1), \tag{19}$$

$$C_{\mathrm{l},n} = \frac{8760(u+0.1)\Delta Lp_{\mathrm{l}}(1+f)^n}{8}. \tag{20}$$

Because of the complexity of the financial package of the project, e.g., terms of loan payment, loan-equity ratio and so on, this study assumes that all investments come from equity. The cash flow expression of Eq. (21) is formulated by substituting from Eqs. (10) and (20) into Eq. (1). The expression of net present value, NPV, as a function of the annual cash-flow, CF_n and the difference of the steam-engine rice-mill investment and electrical rice-mill investment, $\Delta\mathrm{INV}$, is given in Eq. (23).

$$\begin{aligned}\mathrm{CF}_n = {} & S[12p_{\mathrm{ed}}\Delta e_{\mathrm{d}} + 365p_{\mathrm{ee}}u(1+f_{\mathrm{e}})^n\Delta e_{\mathrm{e}}] - \frac{365S\Delta e_{\mathrm{e}}u[p_{\mathrm{h}}(1+f)^n]}{\eta_{\mathrm{th}}\mathrm{LHV_w}} \\ & - 365S\Delta e_{\mathrm{e}}u[p_{\mathrm{om}}(1+f)^n] - \frac{8760(u+0.1)\Delta Lp_{\mathrm{l}}(1+f)^n}{8},\end{aligned} \tag{21}$$

$$\Delta\mathrm{INV} = \mathrm{INV_s} - \mathrm{INV_e}, \tag{22}$$

$$\mathrm{NPV} = -(\Delta\mathrm{INV}) + \sum_{n=1}^{N} \frac{\mathrm{CF}_n}{(1+r)^n}. \tag{23}$$

When NPV = 0, the discount rate, r is known as the internal rate of return, IRR. Then Eq. (23) can be rearranged as

$$\Delta\mathrm{INV} = \sum_{n=1}^{N} \frac{\mathrm{CF}_n}{(1+\mathrm{IRR})^n}, \tag{24}$$

$$\begin{aligned}\Delta\mathrm{INV} = \sum_{n=1}^{N} \Bigg\{ \frac{1}{(1+\mathrm{IRR})^n} \Bigg\{ & S[12 p_{\mathrm{ed}} \Delta e_{\mathrm{d}} + 365 p_{\mathrm{ee}} u (1+f_{\mathrm{e}})^n \Delta e_{\mathrm{e}}] \\ & - \frac{365 S \Delta e_{\mathrm{e}} u [p_{\mathrm{h}} (1+f)^n]}{\eta_{\mathrm{th}} \mathrm{LHV}_{\mathrm{w}}} - 365 S \Delta e_{\mathrm{e}} u [p_{\mathrm{om}} (1+f)^n] \\ & - \frac{8760 (u+0.1) \Delta L p_{\mathrm{l}} (1+f)^n}{8} \Bigg\} \Bigg\}. \end{aligned} \tag{25}$$

The saving of electricity consumption by using rice husk as an energy source contributes to a reduction of carbon-dioxide emissions. The reduction of carbon-dioxide emissions for the entire project life is calculated from the saving of electricity, as given in Eq. (26).

$$CO_2 = \frac{N E e_{CO_2}}{1000}. \tag{26}$$

The model was developed as an Excel spreadsheet computer-based model: it comprises six spreadsheets. One of those spreadsheets is presented in Fig. 1.

Mill General Data						
Project Name		Example1		Wage Rate	150	THB/day
Mill Size		120	$\mathrm{Ton_{paddy}}$/day	Inflation rate	2	%
Life Span		15	Year			
Mill Use Factor		60	%			
Husk Data						
Husk : Paddy Ratio		22	%			
Heating Value	4	000	kW-hr/ton			
Moisture Content (wet basis)		10	%			
Husk selling price	1	50	THB/ton			
Husk inflation rate		2	% per year			
Mill Technical Data						
Base Case (Electrical Rice Mill)						
Mill Specific Electric Demand		2.7	kW/$\mathrm{Ton_{paddy}}$/day	Investment	14449	1000 THB
Elec Consumption to process 1 $\mathrm{ton_{paddy}}$		43.07	kW-hr/$\mathrm{Ton_{paddy}}$			
Number of Operator		4	People			
Steam Engine Rice Mill						
Mill Specific Elec Power Demand		1.64	kW/$\mathrm{Ton_{paddy}}$/day	Investment	19250	1000 THB
Elec. Consumption to process 1 $\mathrm{Ton_{paddy}}$		22.75	kW-hr/$\mathrm{Ton_{paddy}}$			
Energy Conversion Efficiency		5	%	Maintenance Inflation Rate	2	%
Number of Operator		7	People	O&M rate	100	THB/1000 kW-hr
Electricity Price Data						
Demand Charge (includes VAT 7%)		237.005	THB/kW			
Energy Charge (includes VAT 7%)		2.262194	THB/kW-hr			
Energy Charge Inflation rate		6.17	% per year			
Calculation Result						
IRR		**21.15%**				
NPV		**5,186**	1000 THB			
Pay-Back Period		**5.23**	Year			

Fig. 1. An example of computer-based model spreadsheet.

3. Data collection

To utilize the economic model in finding out the IRR for the investment in steam engines as an energy-saving technology for a rice mill, a great deal of technical and economic data is required. The technical and economical data collections are presented as follow.

3.1. Rice-mill energy-consumption

The EC-Asean Cogen program [4] reported that energy consumption patterns in Thai rice mills may vary, depending on whether the mill is a parboiled rice mill or white rice mill. Simple milling may require 30 $\mathrm{kWh\ t^{-1}}$, while with parboiling included it requires up to about 60 $\mathrm{kWh\ t^{-1}}$.

Sookkumnerd [5] conducted a study of electricity consumption in nine steam engine rice mills and 30 electrical rice mills in the Northeastern part of Thailand. All of them produce white rice. In this study, the rice mill energy consumption data was obtained from [5]. The average specific electricity demand and the average electricity consumption of the electrical rice mill and steam engine rice mill are presented in Table 2.

3.2. Investment in steam engines and electrical rice mills

The investment cost of the rice mill was obtained from vendor quotations. The investment cost of electrical and steam engine rice mills are presented in Fig. 2.

It is clearly presented that investment into a steam engine rice mill is higher than electrical rice mill. The cost of the milling unit of steam engine rice mill without prime mover unit (boiler and steam engine) is on the same level as the cost of the whole electrical rice mill. In the steam engine rice mill, the mills main shaft receives power from the crankshaft of steam engine and transmits mechanical power to various milling equipment by belt drive power transmission. So, the milling equipment must be in the positions which are able to receive the mechanical power from the mill main shaft. In the electrical rice mill, the electrical energy is transmitted to many distributed motors, driving milling equipment through an electric cable. So, the arrangement of the milling unit is very flexible and results in more compact structure than a steam engine rice mill. The smaller structure of electrical rice mill leads to the lower investment cost compared to a steam engine rice mill.

Table 2
The average specific electricity demand and average electricity consumption of the rice mill

Rice mill	Average specific electricity demand ($\mathrm{kW\ t^{-1}\ d}$)	Specific electricity consumption ($\mathrm{kWh\ t^{-1}}$)
Electrical rice mill	2.787	44.781
Steam engine rice mill	1.644	22.754

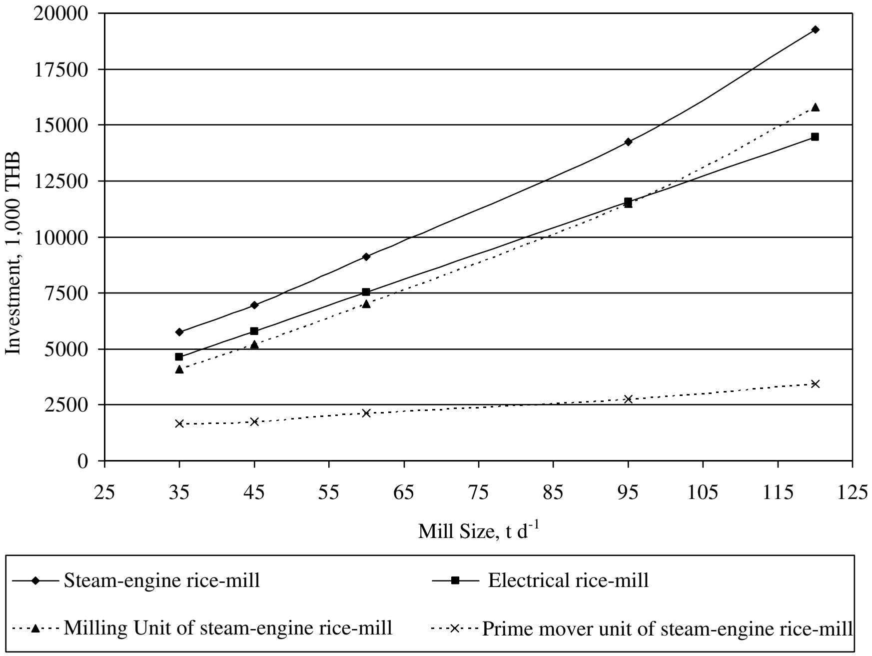

Fig. 2. The investment costs of electrical rice-mill and steam-engine rice-mill.

3.3. Rice husk price

Rice husk can be sold to husk buyers. For the steam-engine rice-mill, some parts of the rice husk must be utilized as fuel for the boiler. The cost due to loss of the opportunity to sell husk was counted as fuel cost in this study. The husk price is reviewed from previous research. The husk price was reported in the range of 100–200 THB t^{-1} [7]. Jungingern [8] reported that husk prices have varied in the past between 56 and 216 THB t^{-1}, though 324 THB t^{-1} in times of extreme rice husk scarcity. In this study, the husk price was assumed to be 150 THB t^{-1}. However, the maximum affordable husk prices at different levels of mill use factors are explored in the next section.

3.4. Steam-engine system's energy-conversion efficiency

This has been reported in various research works. Waddle et al. [9] reported that the conversion efficiency of a 25–150 kW steam-engine system fueled by rice husk is 5%. Ramlimgam et al. [10] reported a conversion efficiency of 6% for a 30 kW steam-engine fueled by rice husk. A conversion efficiency of 7% for a 100 kW steam-engine fueled by rice husk was reported by Mahin [11]. At 5% energy-conversion efficiency, 51.3% of husk must be used as fuel in the mill which corresponds with that in the study by Jungingern et al. [8] which reported that 50–70% of the available husk is utilized as a fuel for the process-energy requirement. In this study, a 5% energy conversion efficiency was used in the analysis.

3.5. Rice husk fuel characteristic

The main characteristics of rice husk are the husk to paddy ratio, HRP, moisture content and lower heating-value. Variations on the fuel characteristics of rice husks have been reported in different studies. The HRP varies from 0.22 to 0.30 [4]. Moisture content and lower heating value from previous researches are summarized in Table 3. In this study, a 10% moisture-content and a 14.4 MJ kg^{-1} LHV were utilized in the analysis.

3.6. Electricity

The price of electricity has a very strong influence on the income of the energy-saving project. For a rice mill size smaller than 120 t d^{-1}, the electricity demand is less than 1000 kW, which is categorized as a medium general service in a Thai electricity-tariff structure. The electrical pricing system for a medium general service is a two-part tariff, which is composed of a demand charge and energy charge. The demand charge is based on the highest 15-min peak demand (kW) in a one month period and the energy charge is based on the electrical energy (kWh) consumed in one month.

Apart from the two-part tariff, electricity consumers must also pay for the "F_t", which reflects the change of the actual cost of electricity generation. The F_t charge is added to the electricity bill on a kWh basis. An example of the electricity tariff for the medium general service on March 3, 2004 is presented in Table 4.

Normally, the basic tariff is seldom changed: only F_t is changed according to the charge of financial status. In this analysis, the electricity tariff comprises two parts. The first part is electricity price-on-demand basis, which directly comes from the demand charge on basic tariff and the second part is electricity price on an energy basis

Table 3
Moisture content and lower heating-value of rice husk

Reference	Moisture (%)	LHV (MJ kg^{-1})
Bhattacharya [12]	12.37	14.48
Therdyothin et al. [13]	8.6	15.8
Bin Abas [14]	5.72	14.16
Mahajan and Mishra [15]	8.92	13.61
EC-Asean Cogen program [4]	10.0	13.2

Table 4
The medium general service electricity-tariff [16]

Voltage level (kV)	Basic tariff		F_t (THB kWh^{-1})
	Demand charge (THB kW^{-1})	Energy charge (THB kWh^{-1})	
>69	175.70	1.6660	0.328
22–33	196.26	1.7034	0.328
<22	221.50	1.7314	0.328

which is the summation of energy charge on the basic tariff and F_t. By this consideration, the electricity price on an demand basis is fixed. Only the electricity price on an energy basis part is changed. From the historical data, from 2000 to 2004, the electricity on energy basis increased at 6.17% annual growth rate. The electricity consumers must also pay for the value added tax (VAT), which is 7% of the total electricity charge.

The carbon-dioxide emission factor for using electricity, e_{CO_2}, was calculated from the fuel consumption for electricity generation and distribution. It was found that the carbon-dioxide emission factor, e_{CO_2}, is 0.5230 kg/kWh.

4. Results and discussion

In this study, rice mills' outputs from 35 to 120 t d^{-1} were used as case studies. The technical and economic parameters used in the analysis are shown in Table 5. The investment data were used from Fig. 2. The economic model developed in the previous section was used to determine the IRR.

Table 5
Technical and economic parameters of electrical and steam-engine rice-mill

Parameter			Unit
Rice husk			
Husk to paddy ratio	HRP	1:0.22	
Lower heating-value dry basis	LHV_d	4000	kWh t^{-1}
Moisture content (wet basis)	MC_w	0.10	decimal
Husk price at the year 0	$P_{h,0}$	150	THB t^{-1}
Electrical rice-mill			
Mill's specific electricity-demand	$e_{d,e}$	2.70	kW t^{-1} d
Mill's specific electricity-consumption	$e_{e,e}$	43.07	kWh t^{-1}
Operation staff	L_e	4	person
Steam-engine rice-mill			
Mill's specific electricity-demand	$e_{d,s}$	1.64	kW t^{-1} d
Mill's specific electricity-consumption	$e_{e,s}$	22.75	kWh t^{-1}
Operation staff	L_s	7	person
Energy-conversion efficiency	η_{th}	0.05	decimal
Operation and maintenance rate at the year 0	$p_{om,0}$	100	THB kWh^{-1}
Economic parameters			
Life span	N	15	yr
Mill-use factor	u	0.60	decimal
Inflation rate	f	0.02	decimal
Wage rate at the year 0	$p_{l,0}$	150	THB$(\text{man-day})^{-1}$
Electricity			
Demand charge (excludes VAT 7%)	$p_{d,0}$	221.5	THB kW^{-1}
Energy charge + F_t (excludes VAT 7%)	$p_{e,0}$	2.1142	THB kWh^{-1}
Carbon-dioxide emission-factor	e_{CO_2}	0.5230	kg kWh^{-1}
Energy-charge inflation-rate	f_e	0.0617	decimal

Table 6
The results from developed model

Mill size ($t\ d^{-1}$)	IRR (%)	Pay back period (yrs)	Total saving of electricity (1000 kWh)	Total reduction of CO_2 emissions (ton)
35	3.63	12.98	2336	1222
45	14.14	7.88	3004	1571
60	20.49	5.67	4005	2095
95	26.60	4.30	6341	3317
120	21.15	5.23	8010	4189

Values of the technical and economical parameters were put into the developed model. The IRRs on the investment of various sizes of steam-engine rice-mills from 35 to 120 $t\ d^{-1}$ are presented in Table 6. Pay-back period, total saving of electricity and total reduction of CO_2 emission were also calculated and presented in Table 6. It was found that the IRRs increase from 3.63% for 35 $t\ d^{-1}$ rice mill to 26.60% for 95 $t\ d^{-1}$. The increase of electricity saving in the bigger rice-mills increases project income and results in increasing IRRs of the project. However, when the rice-mill size increases from 95 to the 120 $t\ d^{-1}$, the IRR of the 120 $t\ d^{-1}$ rice mill becomes less than the IRR of the 95 $t\ d^{-1}$ rice mill. This indicates that the additional specific investment ($\Delta INV/S$) is very much increased from 28,295 THB $t^{-1}\ d$ for the 95 $t\ d^{-1}$ rice-mill to 40,008 THB $t^{-1}\ d$ for the 120 $t\ d^{-1}$ rice-mill, whereas the additional specific investment of 35, 45 and 60 $t^{-1}\ d$ are almost at the same level at 32,229, 25,800 and 26,767 THB $t^{-1}\ d$, respectively. The higher additional specific investment requires higher income to compensate the higher investment and results in a lower IRR.

According to the loan interest-rate offered by Siam Commercial Bank on 4 March 2004, the minimum retail rate, MRR, was 6.25%. If 5% margin is set as the criterion for attractive investment, 11.25% is the minimum IRR to be classified as an attractive investment. From the result presented in Table 6, the IRRs on the investment of rice-mill capacity from 45 to 120 $t\ d^{-1}$, which are higher than 11.25% under the conditions given in Table 5 can be considered as attractive investments.

5. Maximum affordable husk-price analysis

In practice, the highest fluctuating operating parameters are mill-use factor and husk price. Mill-use factor varies by the availability of raw material, i.e. paddies. The husk price depends on demand and supply of rice husk. It is very useful to investigate the effect of the variation of parameters on the IRR. The mill-use factor affects the rice-mill electricity consumption as well as the availability of rice husk. A higher mill-use factor contributes to higher saving of electricity, which is the income of the project. If the mill use factor is too low, the income becomes too low to achieve a high enough return on the investment. If the husk price is very high, the cost due to the loss of opportunity to sell husk is very high and it might be more attractive to select an electrical system and sell all of their rice husks to earn income from the husks.

To analyze the maximum affordable husk price at different levels of mill-use factor, a different approach from the previous analysis was utilized. The target IRR is set, then the husk price and mill-use factor were varied simultaneously while the other parameters were fixed. By this approach, the maximum affordable husk price at different levels of mill-use factor was achieved. The mathematical models describing the maximum affordable husk price at different levels of mill-use factor were developed as explained below.

Eq. (25) was rearranged, to become

$$\begin{aligned}\Delta\mathrm{INV} = {} & 12Sp_{\mathrm{ed}}\Delta e_{\mathrm{d}}\sum_{n=1}^{N}\frac{1}{(1+\mathrm{IRR})^{n}} + 365Su\Delta e_{\mathrm{e}}p_{\mathrm{ee}}\sum_{n=1}^{N}\frac{(1+f_{\mathrm{e}})^{n}}{(1+\mathrm{IRR})^{n}} \\ & - \frac{365Su\Delta e_{\mathrm{e}}p_{\mathrm{h}}}{\eta_{\mathrm{th}}\mathrm{LHV_w}}\sum_{n=1}^{N}\frac{(1+f)^{n}}{(1+\mathrm{IRR})^{n}} - 365Su\Delta e_{\mathrm{e}}p_{\mathrm{om}}\sum_{n=1}^{N}\frac{(1+f)^{n}}{(1+\mathrm{IRR})^{n}} \\ & - 1095u\Delta Lp_{\mathrm{e}}\sum_{n=1}^{N}\frac{(1+f)^{n}}{(1+\mathrm{IRR})^{n}} - 109.5\Delta Lp_{\mathrm{e}}\sum_{n=1}^{N}\frac{(1+f)^{n}}{(1+\mathrm{IRR})^{n}}. \end{aligned} \tag{27}$$

By substituting

$$a = 12p_{\mathrm{ed}}\Delta e_{\mathrm{d}}\sum_{n=1}^{N}\frac{1}{(1+\mathrm{IRR})^{n}}, \tag{28}$$

$$b = 365\Delta e_{\mathrm{e}}p_{\mathrm{ee}}\sum_{n=1}^{N}\frac{(1+f_{\mathrm{e}})^{n}}{(1+\mathrm{IRR})^{n}} - 365\Delta e_{\mathrm{e}}p_{\mathrm{om}}\sum_{n=1}^{N}\frac{(1+f)^{n}}{(1+\mathrm{IRR})^{n}}, \tag{29}$$

$$c = \frac{365\Delta e_{\mathrm{e}}}{\eta_{\mathrm{th}}\mathrm{LHV_w}}\sum_{n=1}^{N}\frac{(1+f)^{n}}{(1+\mathrm{IRR})^{n}}, \tag{30}$$

$$d = 1095\Delta Lp_{\mathrm{e}}\sum_{n=1}^{N}\frac{(1+f)^{n}}{(1+\mathrm{IRR})^{n}}, \tag{31}$$

and

$$e = 109.5\Delta Lp_{\mathrm{e}}\sum_{n=1}^{N}\frac{(1+f)^{n}}{(1+\mathrm{IRR})^{n}}. \tag{32}$$

Eq. (27) can be rewritten as

$$\Delta\mathrm{INV} = aS + bSu - cSup_{\mathrm{h}} - du - e. \tag{33}$$

From Eq. (33), if the rice-mill capacity, S, and the difference of investment between steam engine and electrical-rice mill, ΔINV are specified, only the husk price, p_{h}, and the mill use factor, u, are variable parameters. The target IRR is set to 11.25%, which is 5% above the MRR. Then, the maximum affordable husk-price at different mill-use factors can be obtained. The maximum affordable husk-prices at different mill-use factors for various sizes of rice mill are presented in Fig. 3. At a certain

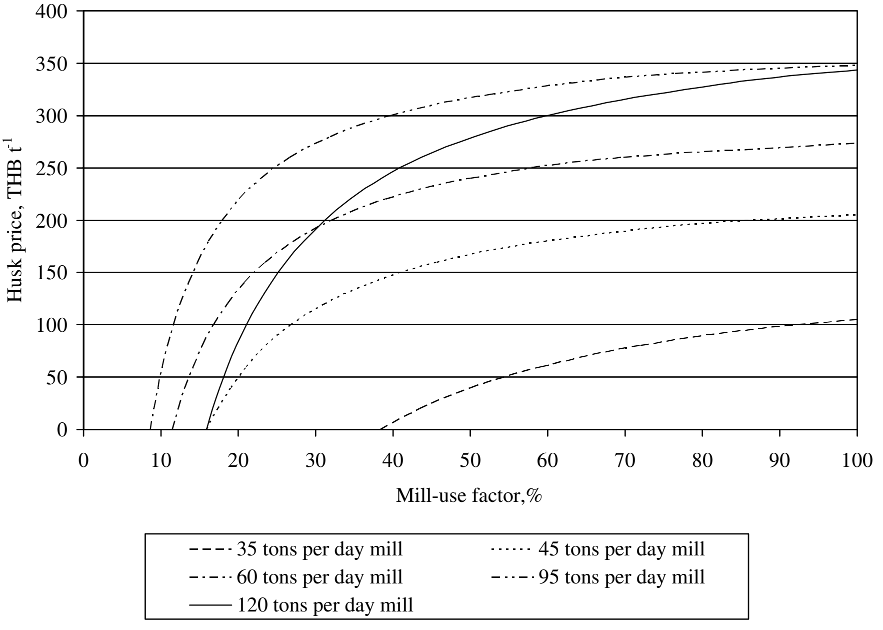

Fig. 3. The maximum affordable husk price for various mill-use factors.

mill-use factor, if the real husk price is higher than the maximum affordable husk-price, the IRR is lower than 11.25%. On the other hand, if the real husk price is lower than the maximum affordable husk price, the IRR is higher than 11.25%.

It can be seen that the higher husk-price requires a higher mill-use factor to reach the target IRR. The larger rice-mill can absorb a higher husk price at the same mill use factor. Fig. 3 can be used as a guideline for rice-mill owners in selecting the appropriate rice-mill system. If they cannot be sure about operating at a high enough mill-use factor at a certain level of husk price, they should select the electrical rice mill and sell all the husk as by-product income. On the other hand, if they are sure that they can operate at a high enough mill-use factor at a certain husk price, they should invest in a steam-engine system and an attractive IRR on their investment can be achieved.

6. Technological options for increasing the economic performance of steam-engine rice-mills

Even the steam-engine rice-mill in the previous analysis gave a very attractive IRR, but the IRR is very sensitive to the husk price as presented in Fig. 3. For 60–120 t d^{-1} rice mills, when the husk price is higher than 250 THB t^{-1}, the required mill-use factor increases very fast to compensate for the higher fuel-cost due to the higher husk price. One approach to reduce the fuel consumption can be by increasing the energy-conversion efficiency of the steam-engine system. The efficiency of the

conventional boiler for steam engine rice mills was reported at 40% [7] which is quite low compared to commercial boilers available in the market. If the conventional boilers are replaced by higher-efficiency boilers, the energy-conversion efficiency of the steam-engine system can be increased and results in a lower fuel consumption.

To investigate the economic performance of a higher-efficiency system, the conventional boiler was replaced by a higher-efficiency boiler, i.e. a traveling-grate stoker water-cooled furnace wall-fired tube-boiler. The technical and economic data of the higher efficiency boiler is given in Table 7. The comparative analysis between the conventional boiler and high efficiency boiler was done for a 120 t d^{-1} system. The maximum affordable husk price for both systems is shown in Fig. 4. It was found that at a husk price lower than 261.03 THB t^{-1} for the 11.25% target IRR, the conventional boiler requires a lower mill-use factor to reach the target IRR. However, when the husk price is higher than 261.03 THB t^{-1}, the higher efficiency system

Table 7
Technical and economic data for a husk-fired traveling-grate stoker water-cooled furnace wall-fired tube-boiler [5]

Boiler capacity (t h^{-1})	Steam pressure (barg)	Efficiency (%)	Investment (1000 THB)
1.30	10	60	3400
2.00	10	60	3800

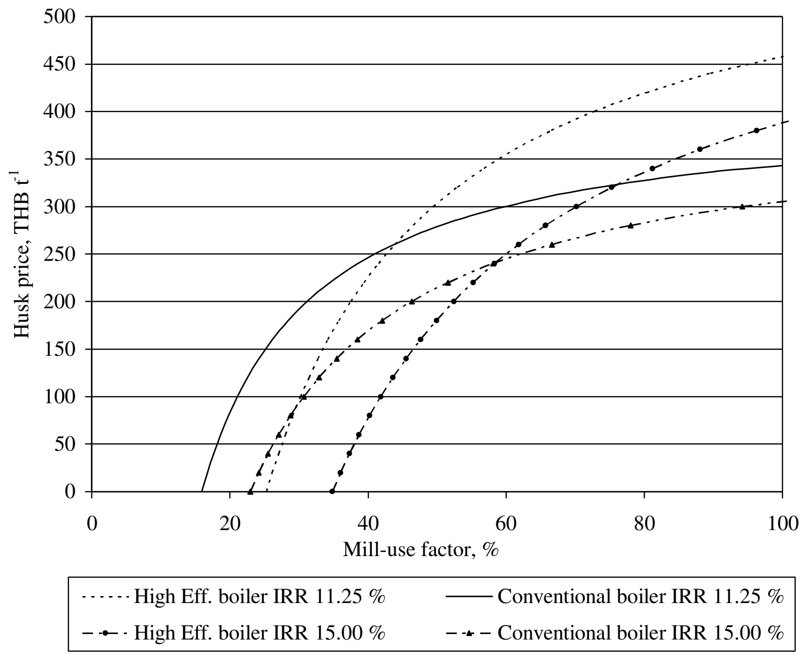

Fig. 4. The maximum affordable husk price for a 120 t d^{-1} rice mill.

requires a lower mill-use factor to reach the target IRR. At 15.00% target IRR, the required mill use factor of the higher efficiency system becomes lower than for a conventional system when the husk price is higher than 240.95 THB t^{-1}. This can be explained by the fact that the fuel cost is reduced for the higher efficiency system, but a higher efficiency system incurs a higher investment. So, if the husk price is not high enough, the higher investment cannot be compensated by increasing the fuel savings. However, when the husk price is higher than a certain level, the increased fuel saving is high enough to compensate for the higher investment.

7. Conclusions

The systematic economic evaluation of the steam engine as an energy-saving technology for a rice mill has been developed. The IRRs on the additional investment of 35–120 t d^{-1} steam-engine rice-mills were determined and the following conclusions drawn.

- Based on the economic and technical data, presented in this study, the use of a steam-engine rice-mill as an energy-saving technology is financially feasible for a rice-mill size from 45 to 120 t d^{-1}.
- The maximum affordable husk prices at different mill sizes were analyzed and assessed. The higher maximum affordable husk price required a higher mill-use factor and a larger mill can absorb a higher husk price than a smaller mill.
- A comparative analysis between a conventional boiler and a higher-efficiency boiler was performed in this study. The economic performance of the higher-efficiency steam-engine system performed better than the conventional system when the husk price is higher than a certain level, for example, at 261.03 THB t^{-1} for the 120 t d^{-1} rice mill at 11.25% target IRR.

8. Recommendations for further study

As described in the previous section, the steam-engine system shows a good return on investment for various sizes of rice mill. However, it has some disadvantages, as compared to the electrical rice-mill. Its disadvantages are as follows.

- The operation of the steam-engine system is difficult. Almost all operations are done manually.
- Due to the lack of good enough combustion control and pollution control equipments, the operation of a steam-engine rice-mill sometimes causes pollution problems, especially particulate matter and black smoke.
- The energy conversion efficiency is quite low.

To promote the steam-engine system as an energy-saving technology for a rice mill, research and development should be focused on improvements to overcome its disadvantages, mentioned above.

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References

[1] Black and Veatch (Thailand). Final report; Thailand biomass-based power generation and cogeneration within small rural industries. Final report submitted to National Energy Policy Office. November 2000.
[2] Department of Alternative Energy Development and Efficiency: Potential of Biomass Energy in Thailand. Available from: http://203.150.24.81/dede/renew/bio_p.htm. March, 2004 [in Thai].
[3] The Center for Biomass Technology. Straw for energy production technology – Environment – Economy, Denmark 1998.
[4] EC-Asean Cogen program: Evaluation of conditions for electricity production based on biomass . Final Report submitted to National Energy Policy Office, Bangkok, Thailand. August 1998.
[5] Sookkumnerd C, et al. The feasibility study of utilization of rice husk as an energy source for rice mills. Final report submitted to Thailand Research Fund. January 2002 [in Thai].
[6] Himakoun, U. Steam Engine in Thailand, The Workshop of ASEN-EC COGEN Program, Medan, Indonesia, November, 5–7, 1991.
[7] Dina Aaager X, Per Thomas Jensen X. Technology development and implementation plan, utilization of rice husk for energy production in thailand. Denmark: Roskilde University; February 2002.
[8] Junginge M et al. Fuel supply strategies for large-scale bio-energy projects in developing countries. Electricity generation from agricultural and forest residues in Northeastern Thailand. Biomass Bioenergy 2001(21):259–75.
[9] Waddle DB, Gowan MM. A technical and investment analysis of intermediate-scale rice-residue conversion systems. National Resources Forum, 1989 in [17].
[10] Ramalingam J, Vellanki RRV. Conversion of firewood-fired boiler to husk-fired boiler. In: Paper presented at the private rice millers training course, RPRDC, Anuradhapura, Sri Lanka. April/May 1997 in [17].
[11] Mahin DB. Power from rice husks. Bioenergy Systems Report. 1986 in [17].
[12] Bhattacharya SC. State-of-the-art of utilising residues and other types of biomass as an energy source. RERIC Int Energy J 1993;15(1):1–21.
[13] Therdyothin A, Bhattacharya SC, Chirarattananon S. Electricity generation potential of Thai sugar-mills. Energy Sources 1992;14:367–80.
[14] Bin Abas I. Rice husk gasification for cogeneration, end-user point-of-view and expectation. Summary report of the COGEN Workshop, Indonesia, November 1991 in [4].
[15] Mahajan KC, Mishra J. Energy from paddy husks – an overview, in energy management. India October–December, 1992:5–14 in [4].
[16] Energy Policy and Planning Office. Available from: http://www.eppo.go.th/power/pw-Rate-PEA-Char.html March, 2004.
[17] Williams EA, Robinson AP. Survey of equipment for small-scale motive power and electricity generation from wood and agricultural residues. Chatham, UK: Natural Resources Institute; 1993.